Comparison of Experimental Measurements and Simulation of Solar (Zeolite4A-Water) Adsorption Refrigerator Using Trnsys and Matlab Softwares

N. O. Omisanya*[,1,a], C. O. Folayan[2,b], S. Y. Aku[2,c], S. S. Adefila[3,d], R. B. O. Suleiman[2,e]

[1]Centre for Automotive Design and Development, Zaria, Nigeria
[2]Mechanical Engineering Department, ABU, Zaria, Nigeria
[3]Chemical Engineering Department, ABU, Zaria, Nigeria

*,[a]ominua@yahoo.com,[b]clementfolayan2002@yahoo.com,[c]syaku@yahoo.com,[d]samadefila@gmail.com, [e]omohu@yahoo.com.

Abstract

In this paper, the design, construction and results of test as well as numerically simulation of a solar powered zeolite 4A-water adsorption refrigeration were presented. The performance of the designed and constructed system was investigated and numerically simulated using Zaria weather data obtained in a typical meteorological year (TMY) format while the design was modeled and simulated using Transient system simulation (TRNSYS) software. The simulation results showed that for a typical year the system recorded appreciable desorbed mass in the range of (0.013-0.23)kg/kg of zeolite moisture content yielding refrigeration effect ranging from (210-9144kJ) within an average desorption time of 245 mins (4hr-5mins). The simulated system achieved an average coefficient of performance (COP) of 0.72, coefficient of performance solar (COPs) of 0.0133, Specific cooling power (SCP) of the order 10.49kW/kg of zeolite, thermal efficiency of 0.836 and exergy efficiency of 52.43%. Comparison of the experimental results and the simulation results showed qualitative agreement and qualitative difference in COP in the range of 1-5% above experimental values.

Keywords

Adsorption System; Zeolite 4A –Water; Experiment; Performance; Simulation

Introduction

The International Institute of Refrigeration (IIR) estimated that approximately 15% of electricity produced across the world is used for refrigeration and air–conditioning of various kinds in 1988, (Lucas, 1988). The developed community depends on stable, reliable grid electricity supply for refrigeration and air-conditioning. Developing countries require stable energy to power refrigeration and air-condition system towards preserving agricultural products, medical care delivery and commerce. In the rural areas where electricity supply is not reliable, the quest for alternative energy for powering cooling systems is inevitable. Thermally activated sorption technology is one of the possible alternatives to electricity drivenvapour compression refrigeration systems. Adsorption cycles have distinct advantage over other heat driven refrigeration cycles in their ability to be driven by heat at relatively low, near environmental temperature, (Yong and Wang, 2006). Since 1980, large effort hasbeen made to improve the performance of the adsorption refrigeration system. Baker (2008) developed the energy and exergy model for ideal adsorption cycle with isothermal beds and no mass recovery to predict the limits to COP enhancement using thermal regeneration.

The models were applied to compare the performance of zeolite-water and silica gel-water adsorbent-refrigerant pairs over a range of maximum bed temperatures. The thermodynamic consistencies of several alternate adsorption property assumptions were quantified. Differences in adsorption characteristics between zeolite-water and silica gel-water result in a significantly larger potential to enhance COP by implementing thermal regeneration for zeolite-water. Based on COP, the zeolite-water pair is preferred when both thermal regeneration and high temperature thermal energy source (>150^{o}C) are used, while the silica gel-water pair is preferred when thermal regeneration is not used and/or a low temperature thermal energy source (<100^{o}C) is used. Florides et al., (2000) modeled and simulated an

absorption solar cooling system using a TRNSYS simulation program and a typical meteorological year file for Nicosia Cyprus. System optimization was carried out in terms of type of collector, size of storage tank, collector slope area. The optimized system consists of a 15m^2 compound parabolic collector tilted at an angle of 30^o from the horizontal and a 600 litres hot water storage tank. The selection of the most appropriate adsorbent–adsorbate pair is one of the important factors determining the efficiency of the adsorption refrigerator. An adsorbent suitable to be employed in adsorption system should have a large adsorption capacity for the selected adsorbate and be easily regenerated regarding the pressure and temperature ranges of operation, whereas a proper adsorbate should have a high latent heat of vapourisation and a suitable boiling point. The lower the temperature at which adsorption occurs relative to the boiling point of the adsorbate is, the larger the latent heat adsorbed will be. Since the desirable lowest adsorption temperature for the adsorption refrigerator is room temperature, the boiling point should be preferentially higher than 20^{o}C. Zeolite–water, Zeolite–methanol, Activated carbon-methanol etc might be mentioned among the adsorbent-adsorbate combination tested, (Critoph, 1988).

Since water has a high latent heat of vaporization and a convenient boiling point, the zeolite-water pair is one of the most preferred adsorbent–adsorbate pairs. However, water has been shown in literature to be a potentially excellent working fluid (available in abundance, non-toxic, corrosion free, low cost, ease of handling it, high latent heat and convenient boiling point for adsorption – desorption cycle) for cooling system, (Shigeighi, 1979). Powering the system directly with solar energy is advantageous with the provision of low energy grade (renewable, abundant, cheap, pollution free and environmentally friendly) in form of heat, which enhances the system efficiency with the direct conversion of the solar heat with minimal losses in the system.

The main aim of this investigation is to evaluate experimentally the performance of a solar CPC adsorption refrigerator (zeolite4A-water) and to compare the experimental measurements with the theoretical simulation using MATLAB and TRNSYS softwares. In the following, double bed module (high temperature) solar CPC collector powered adsorption refrigerator working with zeolite 4A-water was described and the experimental testing for cooling was presented. The adsorber bed (Copper pipe) was arranged in form of concentric tube, finned with stainless sheet metal and packed with zeolite 4A. Subsequently, theoretical modeling and simulation of the system using MATLAB and TRNSYS was undertaken. The system operation was presented and comparison was made between experimental measurements and numerical simulated results.

Introduction of the Adopted System

The solar powered adsorption refrigerator was designed to achieve cooling by operating on adsorption–desorption principles. The system has no moving parts. Water and highly porous silicon compound (zeolite 4A) wereused as working fluid and adsorbent, respectively. The system consists of the following components as shown in Figure 2.1; solar concentrating parabolic collector (CPC), condenser, flooded evaporator, airtight cap (valve) and control valve. The operation concept is based on the fact that when cool (at night) the zeolite acts like a sponge soaking up or adsorbing the water vapour and when heated during the daytime water vapour is desorbed or released.

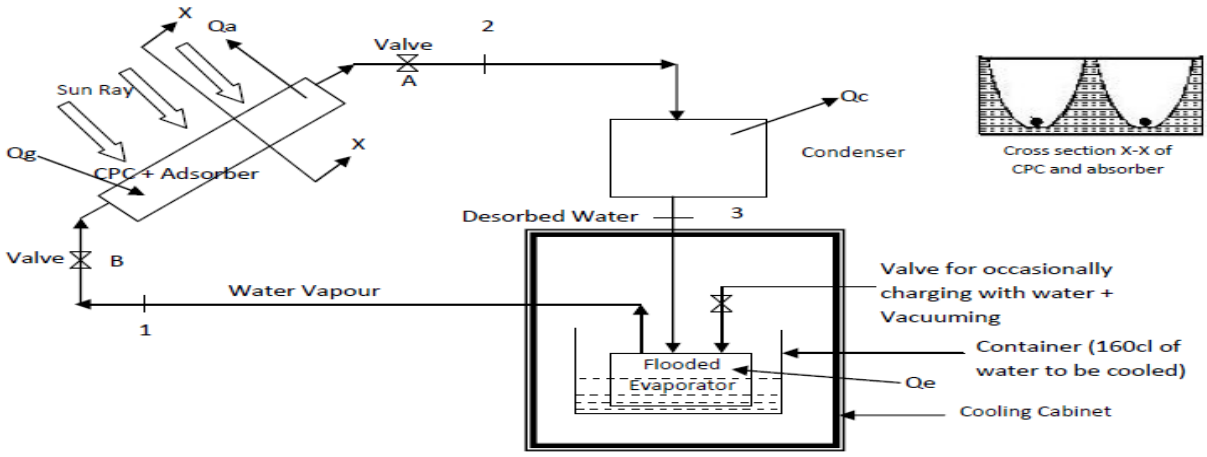

FIGURE 2.1 ADSORPTION REFRIGERATOR DESIGN FLOW DIAGRAMS

The system operates under a partial vacuum, and the water vapour moves with high efficiency under low pressure. At the desorption temperature of water, water vapour begins to desorb from the zeolite. Thus the receiver acts as a boiler and the water vapour leaves through the perforated holes on the duct to the condenser. This water vapour is condensed into water droplets as heat is given off by the heat exchanger (condenser) as depicted in the flow diagram (Figure 2.1). The resulting water runs down due to gravity into a sealed flooded evaporator inside the refrigerator compartment. During the night, zeolite is cooled to temperature closed to the ambient temperature and starts adsorbing water vapour. The liquid water in the storage tank (an evaporator) adsorbs heat from the space to be cooled and is converted into water vapour. Since the system is sealed under very low pressure the remaining water in the evaporator (flooded) box freeze's into ice. This ice will melt slowly during the next day thus providing sustained cooling at reasonable constant temperature.

The acquired variety of zeolite is 3mm diameter spherical pelletisedzeolite 4A from Grace Davison USA (SYLOBEAD 513 Molecular). The specifications of the refrigerator collector are as follows:

(1) Collector Housing:

Structure	CPC design
Size (mm)	1340x831x459
Material	Wood/Plywood/Ceiling board

(2) Collector Area

Aperture area (m^2)	1.029

(3) Absorber

Material	Copper tube
Diameter (mm)	42
Tube coating	black
Absorption coefficient	>0.94
Emissivity	<0.07
Mirror surface	ReflecTech (Silver-Metalised) mirror film

(4) Transparent Cover

Material	Low Iron glass
Thickness (mm)	4
Number	Double

(5) Insulation

Material	Fibre glass

System Assembly

The schematic diagram of the design system is shown in Figure 2.2. The finned vapour draining pipe was initially inserted into the receiver pipe.

After which, one end of the receivers was closed by brazing a plate. Filling of the receiver tube with pelletised zeolite 4A was done through the open end of the receiver pipe (Pelletized zeolite 4A packed in the spaces between the two pipes) with continuous vibration to allow for proper settling of the pellet thus preventing void. The ends of the receiver pipe were then closed and later brazed to prevent any vapour pressure loss from the system. The collector and the receiver were coupled appropriately and the whole was mounted on top of a table with an inclination of 11.2° E-W (Zaria latitude) under which was located the cooling box which accommodates the evaporator (Plate 2.1).

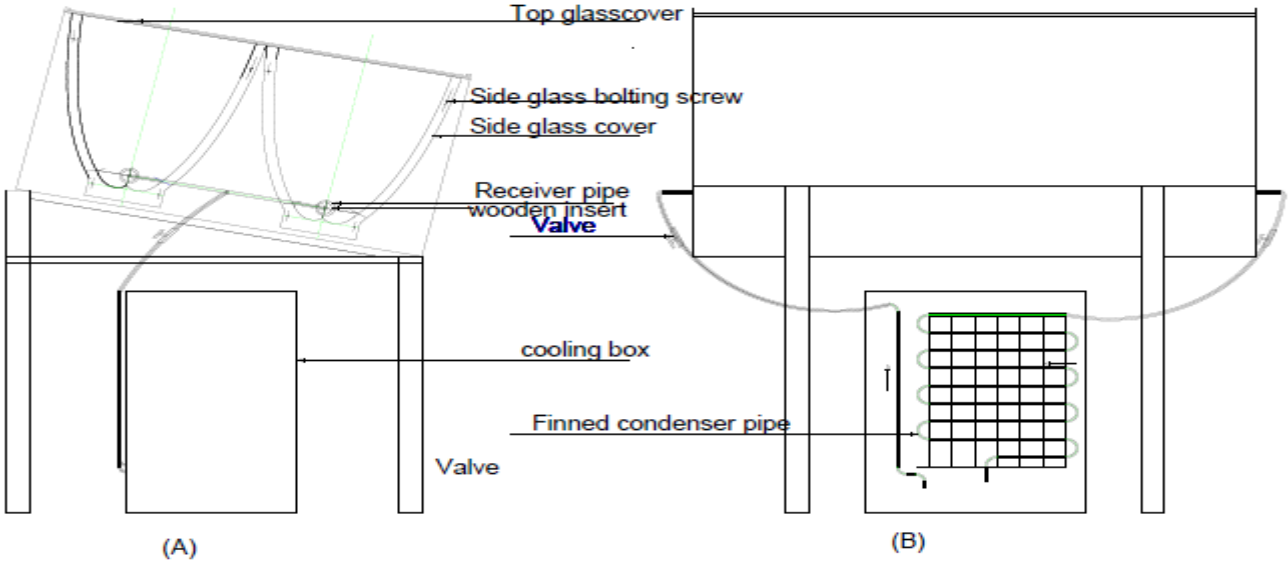

FIGURE 2.2 SCHEMATICS DRAWING OF THE SYSTEM DESIGN: ((A) SIDE VIEW, (B) BACK VIEW)

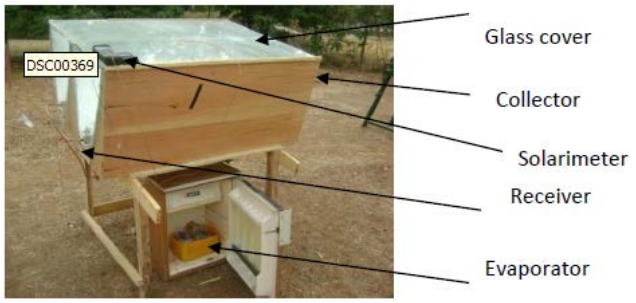

PLATE 2.1 SYSTEM SETUP (EVAPORATOR VIEW)

The solar collector (CPC) with aperture area of 1.029m^2 has the receiver tube (of length 1340mm) with the ends mounted with a plywood suspension inserted in the side glass cover. The water vapour draining pipe from each of the adsorber was linked (by brazing) and connected to the condenser and evaporator appropriately,(Figure 2.2). The experimental setup is as depicted in Plate 2.1 with a designed cooling capacity of 102.93W.

Test Procedure (Starting off the System)

The tests were carried out in the months of April 2011 at the Mechanical Engineering Department, Ahmadu Bello University Samaru, Zaria. The system was setup as shown in Figure 2.2 with corresponding picture in Plate 2.1. One end of each of the six thermocouples was glued to the surface of the adsorber tube, condenser pipe, evaporator box, glass cover, cooling box interior wall while the last wire was hung freely in the air (ambient). The other ends were soldered to the input point on a switch with its output connected to the voltmeter. Charging of the system commenced at 4.00pm with the filling of the evaporator (flooded) box with 75cm^3 of distilled water. After which the evaporator (box) tank valve was connected to an electrically controlled vacuum pump (2.85hp, 0.3A) while the two hand valves were open. On starting the pump, the machine sucked out much of the air in the system. As soon as the vacuum pump gauge indicated 760mm Hg, this was immediately followed with the valve replacement and tightening simultaneously with the removal of the vacuum pump. At this stage, the system was in a vacuum state ready for operation. With the aid of the switch and the thermocouple meter, the readings from the system glued surfaces were taken from the voltmeter (Gonzalez and Rodriguez, 2007). The tube surface temperature of the adsorber/generator (T_a/T_g), the condenser (T_c), the evaporator (T_e) the ambient air temperature (T_{amb}), cooling box interior wall (T_w) and the glass cover surface (T_s) were measured using copper– constantan thermocouples. The global solar radiation (I_r) in the plane of the collector was measured using the Daystar pyranometer. The thermocouple meter and the solarimeter were placed in the plane of the collector, side by side since simultaneous reading was required. Moreover, each temperature reading required turning the switch. This was followed with the locking of valve A (valve leading to the condenser) and opening of valve B (valve leading to the evaporator). The alternate opening and closing of valves A and B was repeated everyday at 8.00am and 16.00pm respectively. The readings were taken for a period of 2weeks (1 to 14 of April 2011). The loading of the cooling cabinet was achieved by pouring some quantity of water (say 160cl) as product to be refrigerated into the container containing the evaporator box.

Refrigerator Coefficient of Performance

1) Cycle COP

For an intermittent adsorption cycle, the assessment parameter is the coefficient of performance (COP) defined as the ratio of the cooling effect to the total energy supplied for the desired cooling effect. (Anyanwu and Ogueke, 2003).

$$COP_1 = \frac{Q_e}{Q_g} = \frac{T_e(T_g - T_a)}{T_g(T_c - T_e)} \approx \frac{T_e}{T_g} \qquad (2.1)$$

Where Q_e and Q_g are the heat transfer during refrigeration and the heat used to generate refrigerant during generation, respectively. However, for the actual experimental COPcycle

$$COP_{cycle} = \frac{Q_e}{Q_t} = \frac{\sum\left(\overline{m}_{reg} C_{pref} \Delta T \Delta t\right)_{ev}}{\sum_{a+b}\left(\overline{m}_{ref} C_{pref} \Delta T \Delta t\right)_{bed}}, \qquad (2.2)$$

The total energy input to the system Q_t= $Q_{a(isosteric)}$+ $Q_{b(desorption)}$

2) Solar COP

The system is intermittent, and in solar powered adsorption machines, the solar COP is usually defined as

$$COP_s = \frac{\Delta m\left\lfloor L - c_p(T_c - T_e)\right\rfloor}{S\int_{sunrise}^{sunset} I(t)dt} \qquad (2.3)$$

where c_p is the specific heat of the liquid refrigerant, L is its vapourisation latent heat, Δm is the evaporated refrigerant mass, S is the collector area and I is the irradiance. Therefore, equations 2.1 and 2.2 were used in evaluating the theoretical and actual experimental COP cycle for the system respectively using the measured temperatures

couple with D-A equation 3.10.

3) *Specific Cooling Power (SCP)*

Specific cooling power indicates the size of the system as it measures the cooling output per unit mass of adsorbent per unit time. The time is the cycle time (s) which is the length of time for a full cycle which means a complete cycle of adsorption and desorption in one of the adsorbent beds. Higher SCP value indicates the compactness of the system.

$$\text{SCP} = \frac{Cooling\ effect}{Cycle\ time\ per\ unit\ adsorbent\ mass} = \frac{Q_e}{m_z x t_{cycle}} = \frac{m_{rg} C_{pr}(\Delta T)}{m_z x t_{cycle}} \quad (2.4)$$

4) *Exergy Efficiency (Thermodynamic Efficiency)*

The thermodynamic efficiency (exergetic efficiency) relates the actual performance of a system to its expected maximum performance as compared to its ideal Carnot cycle. For adsorption refrigeration system exergy efficiency can be written from a relation proposed by Pons et al., (1999) as follows;

$$Exergyefficiency\varepsilon = \frac{COP_{adsys}}{COP_{\max}} \quad (2.5)$$

$$COP_{\max} = \left(\frac{1-\left(T_{adsor}/T_{gen}\right)}{\left(T_{adsor}/T_{evap}\right)-1} \right), \quad (2.6)$$

$$COP_{adsys} = \frac{\bar{Q}_{evap}}{\bar{Q}_{gen}}, \quad (2.7)$$

Where Q_{evap} and Q_{gen} are the heat transfer during refrigeration and heat used to generate refrigerant during generation.

Modeling and Simulation of Adsorption Refrigeration

The simulation of model include modeling (mathematical analyses) and simulation of adsorption refrigeration cycle using Matlab code as well as simulation of solar (zeolite – water) adsorption refrigeration system in TRNSYS environment using readable MATLAB code. The basic sorption cooling cycle is composed of four steps (Figure 3.1), namely (a) Isosteric heating (b) Isobaric desorption (c) Isosteric cooling and (d) isobaric sorption. During the phase (a) and (b) heat is supplied to the sorbent bed by heating the adsorber fluid. The water desorbed from the bed flow to the condenser. During the cooling cycle;[Phase (c) and(d)] the heat is transferred from the evaporator to the adsorber. Being a sorption system using an array of two-CPC collector bed containing pelletized zeolite 4A, development of a simplified model was done which include the thermal capacities of various components and consider the adsorption unit. In order to simplify the simulation each component (adsorbent bed, condenser and evaporator) is considered to be homogeneous.

Mathematical Modeling of Refrigeration Cycle

The adsorption refrigeration cycle described in section 2.0 to 2.2 is modelled using the equations below. According to the Clapeyron diagram the cycle can be thermodynamically modelled as stated in equations 3.1 to 3.6. Starting from point 1 as shown in Figure 3.1 the input heat to the adsorbent bed for isosteric heating (1→2)

$$Q_{ih} = m_z\left(c_{p_z} + c_{p_w} W_{\max}\right)\left(T_{g1} - T_{g2}\right), \quad (3.1)$$

where m_z is the mass of zeolite (kg), c_{pz} is the specific heat of zeolite kJ/kgK, c_{pw} is the specific heat of water adsorbed kJ/kgK, W_{max} is the maximum water adsorbed per kg of adsorbent.

The heat required for the desorption process (2→3) has two components

$$Q_{id} = Q_{des} + Q_{sh}, \quad (3.2)$$

where Q_{des} is the heat of desorption given by

$$Q_{des} = m_z \int_{W_{\max}}^{W_{\min}} \Delta H \partial W \quad (3.3)$$

Where Q_{sh} is the sensible heat of adsorbent plus its adsorbate content evaluatedas

$$Q_{sh} = m_z c_{p_z}(T_{g2} - T_{g1}) + m_w c_{p_w} \int_{T_2}^{T_3} W(T) dT \quad (2.4)$$

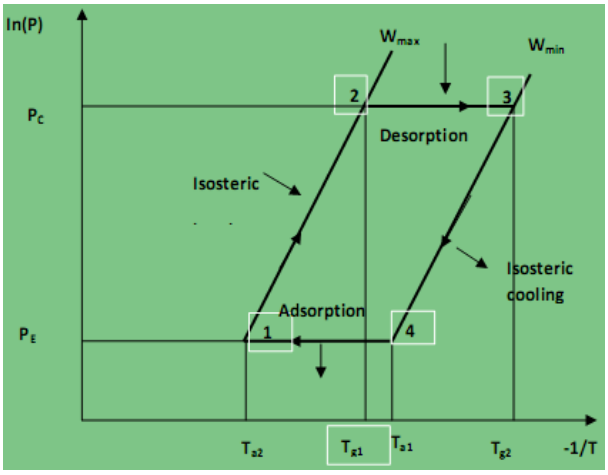

FIGURE 3.1; ADSORPTION REFRIGERATION CYCLE (CLAPEYRON DIAGRAM).

The useful refrigeration effect which is the energy that must be supplied to the evaporator, Q_{ev} is evaluated as the difference between the latent heat of evaporation of the cycle adsorbate and the sensible heat of the adsorbate entering the evaporator at condensation

temperature.

$$Q_{ev} = m_w(W_{\max} - W_{\min})\left[L_{ev}(T_{ev}) - \int_{T_{ev}}^{T_c} c_{p_w}(T)dT \right], \quad (3.5)$$

But L_{ev} is the latent heat of evaporation of water (kJ/kg) c_{pw} specific heat of water in liquid phase which is assumed to be equal to that of water. The coefficient of performance (COP) for the operation evaluated as the ratio of the useful refrigeration effect produced and the heat input to the adsorber.

$$\text{COP} = \frac{Q_{ev}}{Q_{sh}+Q_{id}}, \quad (3.6)$$

The following assumptions are made in evaluating the coefficient of performance COP of basic (zeolite-water) adsorption refrigeration cycle.The specific heat of dry adsorbent (zeolite 4A) is assumed to be constant and taken as 920J/kgK. The specific heat of the adsorbent phase is assumed to be equal to the specific heat of the bulk liquid (water), Pons and Grenier (1986), Critoph (1988). The heat of adsorption is assumed to be equal to that of desorption and it is expressed as (Cacciola et al., 1997).

$$\Delta H(w) = [B_0 + B_1(w) + B_2(w^2) + B_3(w^3)]\frac{R}{MMH_2O}(1000) \quad (3.7)$$

While B_o, B_1, B_2, B_3 are constant and their numerical values are given in Table 3.1. R is the universal constant and MMH_2O is the molar mass of water in kg/kmol.

TABLE 3.1; NUMERICAL COEFFICIENT VALUE FOR EQUATIONS 3.7 TO 3.9 (CACCIOLA, et al., 1997).

A_o=14.8979	B_o=-7698.85
A_1=95.4083	B_1=21498.1
A_2=-636.658	B_2=-184598
A_3=1848.84	B_3=512605

1 Heat of evaporation of water is assumed to be equal to the heat of condensation of water, which is defined as $L(T)=3172x10^3 - 2.4425x10^3(T)$ where T is in Kelvin.

2 The specific heat of the adsorbent, thermal contribution of the adsorbate vapour, metal parts and additive are assumed to be constant.

3 The equilibrium equation relating the amount of water adsorbed, w, pressure of adsorbate P(mbar), at temperature T(K) of zeolite4A-water pair is written as

$$Ln(P) = (A_0 + A_1 + A_2w^2 + A_3w^3) + \frac{(B_0+B_1+B_2w^2+B_3w^3)}{T}, \quad (3.8)$$

(Cacciola et al., 1997), which can be rewritten as

$$Ln(P) = \left(A_0 + \frac{B_0}{T}\right) + w\left(A_1 + \frac{B_1}{T}\right) + w^2\left(A_2 + \frac{B_2}{T}\right) + w^3\left(A_3 + \frac{B_3}{T}\right), \quad (3.9)$$

The values A_1, A_2, A_3 are constant and their numerical values are presented in Table 3.1.

The amount of water (w) desorbed by each adsorber is calculated from a theoretically modified Dubinin – Radushkeuich equilibrium equation for zeolite - water pair, Wang (2001) from the equation

$$w = w_o\exp\left[-k\left(\frac{T}{T_s}-1\right)^n\right], \quad (3.10)$$

where (w) is the equilibrium adsorption capacity of adsorber, k and n are the characteristic parameters of adsorption refrigeration pairs, w_o is the saturated adsorption capacity at $T=T_s$ and $P=P_s$ (where T_s is the saturation temperature at pressure P_s), T is the adsorbent temperature. The equilibrium parameter values for zeolite - water are $w_o = 0.261$, k= 5.36, n= 1.73. (Wang, 2001)

Simulation of an Intermittent Adsorption Refrigeration Cycle

The simulation of the performance of adsorption refrigeration cycle is model with MATLAB using equations 3.1 to 3.9. The calculation involves iterations and appropriate initial, operating boundary conditions were imposed in analyzing and achieving the simulation. The adsorption properties of zeolite – water were tested under the design and operating condition of evaporation temperature from 0^oC to 10^oC, condenser temperature from 40^oC to 25^oC at a given condenser temperature and evaporation temperature respectively. The simulation results generated from the MATLAB code for the intermittent (zeolite-water) adsorption refrigeration cycle (COP with desorption temperature) while varying the evaporator temperature and condenser temperature are presented in Figures 4.1 and 4.2.

Modeling Equations of the Solar Thermal System

Solar collector model in this work is the CPC collector type. The collector efficiency is modelled using first order efficiency equation 3.14 and applying the tested commercial efficiency parameters of CPC collectors. The efficiency of the concentrator collector is expressed as the ratio of the useful energy gain to the incident radiation on the aperture plane.

$$\eta = \frac{Q_u}{AG_T} \quad (3.11)$$

The useful heat delivered by the solar collector Q_u is the energy absorbed (S) by the heat transfer fluid minus the direct or in direct heat losses from the surface to the surrounding.

$$Q_u = A\left[S - \frac{U_L(T_o-T_a)}{C}\right], \quad (3.12)$$

The useful energy can as well be described as the rate of energy being absorbed by the working fluid through the adsorber

$$Q_u = \bar{m}c_p(T_o - T_i), \quad (3.13)$$

Since the loss coefficient is not constant the first order efficiency formula is used based on the collector tested according to ASHRAE standard and rated by SRCC (ASHRAE 2003, SRCC, 1995). The first order efficiency is given as

$$\eta = \frac{Q_u}{AG_T} = \frac{\bar{m}c_p}{AG_T}(T_o - T_i), \quad (3.14)$$

This can be written as

$$\eta = \eta_o - \eta_1\left[\frac{G_T}{T_o - T_{amb}}\right], \quad (3.15)$$

where η_o = is the intercept efficiency, η_1= is the negative first order loss coefficient (kJ/h-m^{2}K) Evaluation of the output temperature from the combination of equations 3.13 and 3.14 yielded

$$T_O = \left[\eta_o G_T + \frac{\bar{m}c_p}{AT_i} + \eta T_{amb}\right] \Big/ \left[\frac{\bar{m}c_p}{A+\eta_1}\right], \quad (3.16)$$

Evaluating equations 3.11 to 3.16 using TRNSYS integrated MATLAB code registered in the deck file the system performance is modelled and simulated in the TRNSYS studio.

Solar Adsorption System (Trnsys Studio) Model

TRNSYS 16 components were used in modeling and simulating the operational performance of the designed solar adsorption refrigerator. This simulation programme has a modular structure that divides the system into a series of components (Types) that are interconnected with each order and compiled through the inter face TRNSYS studio. This TRNSYS Type implements a link with Matlab engine through a Component Object Model (COM) interface. Type 155 can have different calling mode (e.g. iteration component or real time controller). Each component is modeled using mathematical equations programmed in FORTRAN. The mathematical models used in each component can be found in TRNSYS (2007). Each component in Figure 3.2 is represented as a box, which requires a number of constant parameters, time dependent inputs and yielded time dependent outputs. A given output can however be used as an input to any number of other components.

The TRNSYS screen capture of the solar thermal system is presented in Figure 3.2

The components model in this work is;

1 Adsorption unit (CPC collector efficiency and adsorption bed system)

2 Weather data

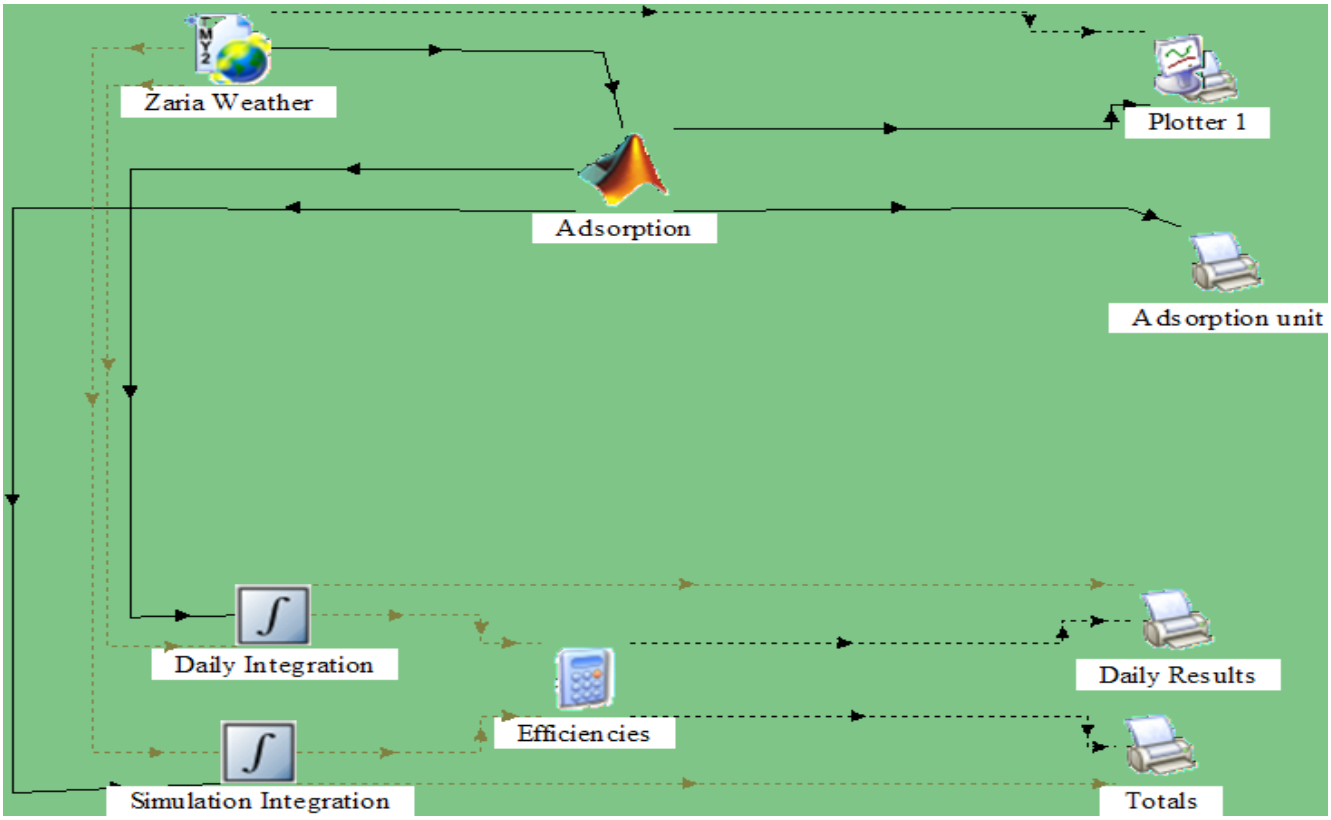

FIGURE 3.2 TRNSYS STUDIO MODEL

1) *Adsorption Unit*

The common approach to model a direct solar adsorption refrigerator system is by using the TRNSYS built in component Type 155 where the collector efficiency is integrated with the adsorption unit while assuming that the collector adsorber output temperature is in equilibrium with the adsorber temperature. The collectors corresponding performance parameters are obtained from commercial solar thermal collector and these parameters are provided in the following subsections. To prevent commercializing this present study the collector manufacturer are not provided. The adsorption unit is written in TRNSYS readable MATLAB code (according to the TRNSYS manual) by integrating the CPC collector efficiency equations (3.10-3.15) and adsorption system equations (3.1-3.10). The adsorption cooling cycle is modeled in MATLAB (Type 155) as m-file. The TRNSYS built in component Type 155 is the component that was used to run MATLAB commands (the m-file will be call at each call to MATLAB). In this work, the component is used for the computation of solar thermal collector efficiency equations (3.11 to 3.16) and the adsorption equations. The efficiencies (Equa) shown in the studio has the formulation to calculate the system efficiency (daily and total), Plotter (Type 65) shows the expected output on the screen, while adsorption unit (Type 25) write the expected output to specified Microsoft Excel file. Applied as model parameter is solar CPC collector area of 1.029m^2 and the collector is oriented to 11.2^o (Zaria latitude) along the East-West direction. In modeling the collector, the following efficiency parameters of tested commercially available CPC collectors were used in addition to the collector design parameter, Table 3.2.

TABLE 3.2 COMMERCIAL EFFICIENCY PARAMETERS

N/s	Parameters	Value/unit
1	Intercept efficiency	0.8
2	First order loss coefficient	2.7W/m^{2}K
3	Second order loss coefficient	0.08W/m^{2}K^2
4	Tested flow rate	0.05m^3/s
5	Specific heat of working fluid	4.190kJ/kgK

2) *Weather Data*

The solar radiation is required to estimate the thermal performance of the system in the long term. In this work, the climate database gotten from www.weatheranalytics.com was used for the simulation. This was model using the information provided by the meteorological data of Zaria, Nigeria (11.2N latitude, 7.4E longitude) obtained in a Typical Meteorological Year, (TMY) file format. Finally, the model was simulated using the recommended typical year simulation time as in Duffie and Beckmann (2006) by using the hours of the mean day of each month of a typical year.

Results and Discussion

Simulation Results for the Refrigeration Cycle

The results from the MATLAB code for the intermittent zeolite 4A-water adsorption cycle (COP with desorption temperature) while varying the evaporation temperature and condenser temperature are presented in Figures 4.1 and 4.2. According to the results in Figure 4.1, the profile increases to a peak and assumed a constant level. For a given condenser temperature (30^{o}C) the COP decreases for a given evaporator temperature. For zeolite 4A –water this implies that higher desorption temperature is needed for the same value of COP for a given evaporation temperature.

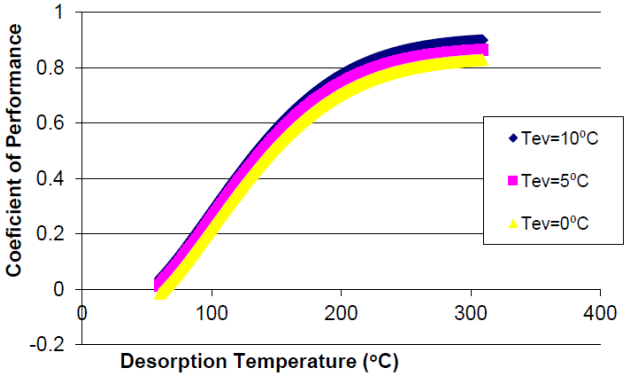

FIGURE 4.1 VARIATION OF COP WITH DESORPTION TEMPERATURE AT CONSTANT TCOND=30^{o}C

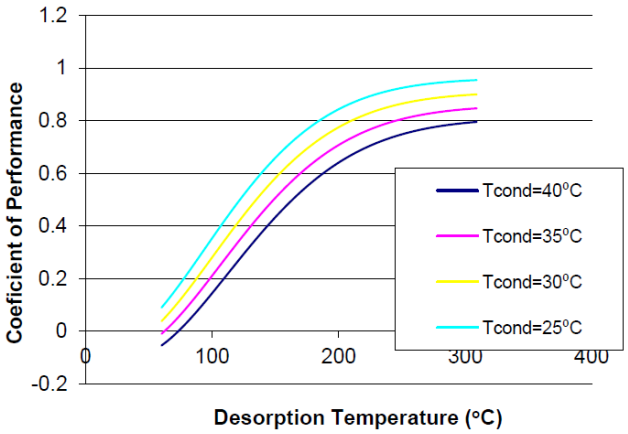

FIGURE 4.2 VARIATION OF COP WITH DESORPTION TEMPERATURE AT CONSTANT TEV=10^{o}C

The interpretation of this is that the energy needed to

raise the temperature increases as shown in Figure 4.1 with the higher desorption temperature. The variation of COP as the condenser temperature changes for a given evaporator temperature is presented in Figure 4.2. As the condenser temperature increases for a given constant evaporation temperature (0°C) higher desorption temperature is required.

Discussion of Simulated Results for the CPC Energised Adsorption System

Figure 4.3-4.11 shows the results obtained using the TRNSYS and MATLAB softwares for the zeolite4A-water adsorption refrigerator. The weather data used were those for Zaria for a typical year. The system is powered by exposing the adsorbent bed contained in the tubular receiver directly to solar radiation concentrated by the CPC collector. Figure 4.3 shows the variation of coefficient of performance with desorption temperature of 17 January for a typical year in Zaria. 17 January is the recommended mean for January by Duffie and Beckmann, (2006). The coefficient of performance solar (COPs) increases with increase in desorption temperature starting from about 50°C to a peak value (COPs of 0.015 at desorption temperature of 150°C) as shown in Figure 4.3. This implies that there exist a maximum COPs with increasing desorption temperature. The cycle coefficient of performance increases with increase in desorption temperature.

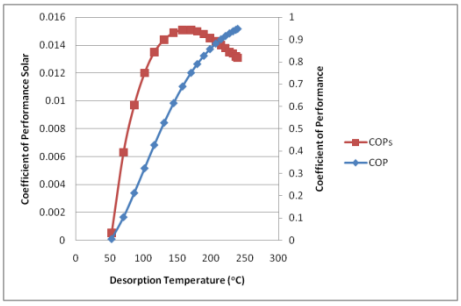

FIGURE 4.3; VARIATION OF COEFFICIENT OF PERFORMANCE WITH DESORPTION TEMPERATURE (17JANUARY CYCLE)

Figure 4.4 shows the variation of adsorber bed temperature and zeolite moisture content with time for a typical year in Zaria. The adsorber bed initially gains sensible heat which increases with time. As desorption of water vapour started, the water vapour content in the zeolite reduces to a minimum level with time. This implies that at the minimum level further increase in adsorber bed temperature desorbs no moisture. Figure 4.5 depicts the variation of useful energy and insolation with time for a typical year in Zaria. The useful energy and insolation increases to a maximum point and the profile took the form of a dome shape with the peak at solar noon. This implies that useful energy gain by adsorber bed is proportional to the insolation. Figure 4.6 shows the variation of adsorber temperature, ambient temperature and insolation with time for a typical year in Zaria. Here also the adsorber bed temperature is proportional to the insolation but the ambient temperature is relatively proportional to insolaion. The interpretation is that fluctuations in weather resulted in energy loss that leads to disagreement shown in the ambient temperature.

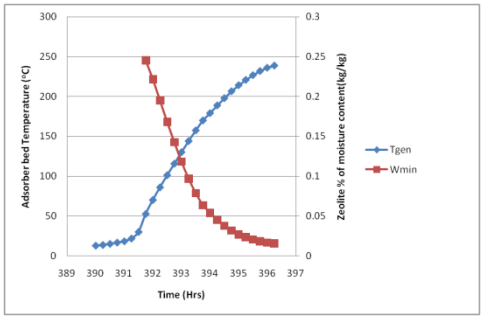

FIGURE 4.4; VARIATION OF ADSORBER BED TEMPERATURE (TGEN) AND ZEOLITE MOISTURE CONTENT (WMIN) WITH TIME (17JANUARY CYCLE)

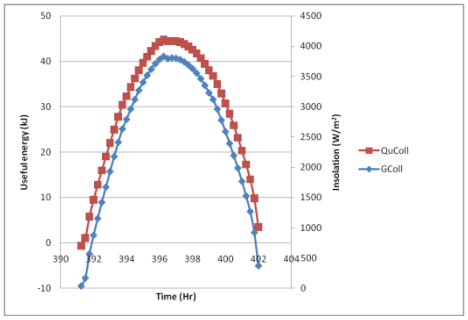

FIGURE 4.5 VARIATION OF USEFUL ENERGY (QUCOLL) AND INSOLATION (GCOLL) WITH TIME (17 JANUARY CYCLE)

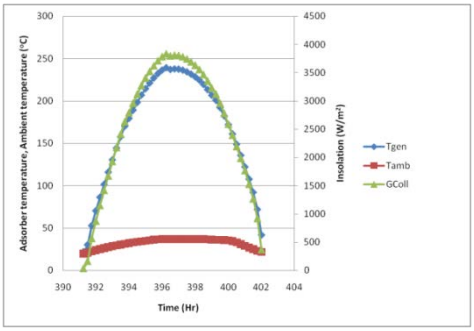

FIGURE 4.6 VARIATION OF ADSORBER (TGEN) AMBIENT TEMPERATURE (TAMB) AND INSOLATION (GCOLL) WITH TIME (17 JANUARY CYCLE)

Using the mean day for each month as recommended by Duffie and Beckman (2006), a whole year variation of the simulated peak adsorber (desorption) temperature and peak insolation for a typical year in Zaria is plotted as showed in Figure 4.7. This revealed the fluctuation in weather data used in the simulation.

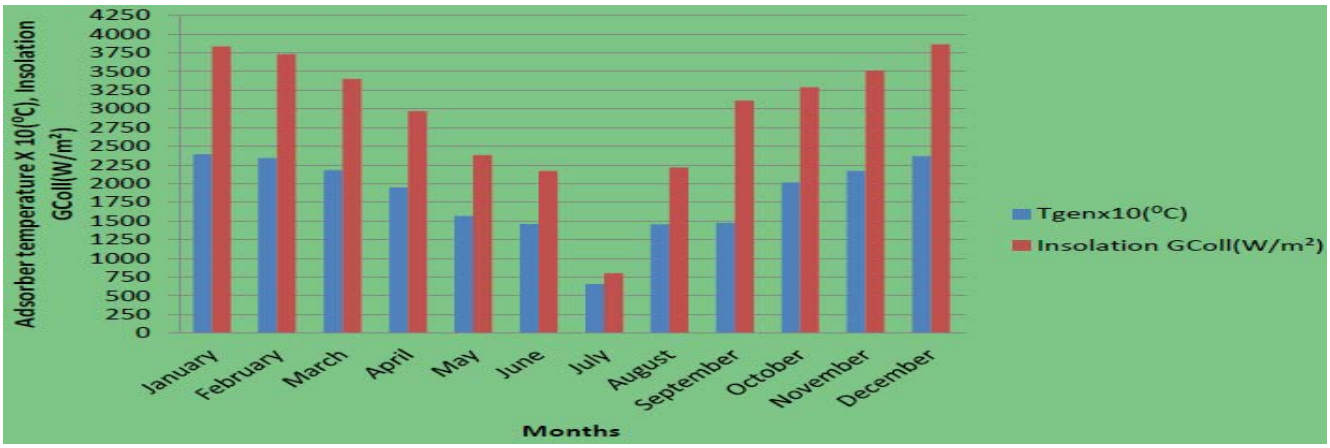

FIGURE 4.7 VARIATION OF ADSORBER TEMPERATURE AND INSOLATION WITH MONTHS FOR THE WHOLE YEAR FOR A TYPICAL YEAR IN ZARIA

On the average, the heating of the adsorber bed starts at about 7.30am while desorption starts at about 8.30am and it reachs a maximum generation temperature between the hours of 11.30am-13.30pm. The isosteric heating phase coincides with 7.00-8.30am when the adsorber bed continuously adsorbed the solar radiation. The generation temperature increases as shown in Figure 4.4 from about 16°C to 55°C within a period of 1hr 30mins after which desorption of water vapour from zeolite commenced. The highest adsorber temperature of 238°C was recorded in the month of January (high insolation month) for Zaria weather while the least temperature of 65°C was recorded for the month of August (low insolation month). The system operation resulted in appreciable desorbed mass in the range of (0.013-0.230) kg/kg of zeolite. This percentage of moisture yield has a refrigeration effect ranging from (210-9144kJ) within an average desorption time of 245mins (4hr5mins). The simulated system achieved an average cooling performance COP of 0.72, COPs of 0.0133, SCP of 10.49kW/kg of zeolite. The efficiency of heating process was 0.836 and the exergetic efficiency was 52.43%.

Comparison of Experimental and Simulated Results

Experiments have been performed to investigate several cycles of a typical year in Zaria and experimental days of 1 to 14 April. The maximum values of the average temperature of the bed T_{max} changes in the range of 120-220°C while minimum changes recorded is in the range of 20-25°C. Comparing simulated results for a typical day (1 April) with that of experimental day (1 April 2011) are presented in Figures 4.8 and 4.9. Figure 4.8 shows the variation of simulated and experimental result of adsorber temperature and insolation with time.

The dynamic behaviours of the temperature and insolation during the complete cycle werererevealed. The discrepancy in the simulated and experimental results is not surprising. It is due to the fluctuations in the weather during the experimental measurements. However, the direct exposure of the adsorbent bed contained tubular receiver of the CPC collector to solar radiation is advantageous in the performance of the system by minimizing the losses from the tube to the adsorbent and adsorbate thus enhancing desorption.

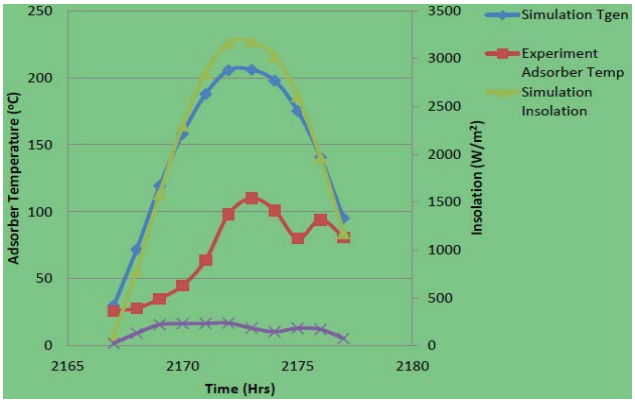

FIGURE 4.8 VARIATION OF ADSORBER TEMPERATURE AND INSOLATION OF SIMULATION AND EXPERIMENT WITH TIME (1 APRIL CYCLE) AT T_{CON}=30°C T_{EV} =10°C.

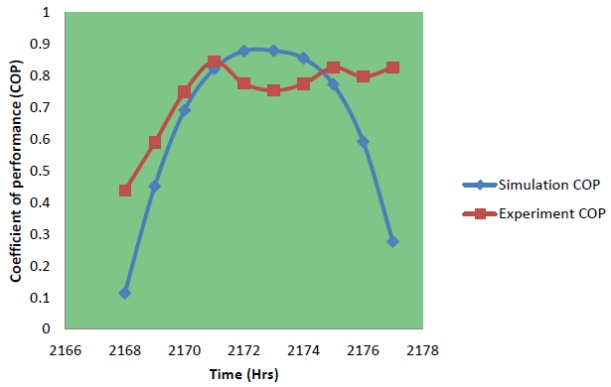

FIGURE 4.9 VARIATION OF COP OF SIMULATION AND EXPERIMENT WITH TIME (1 APRIL CYCLE) AT T_{CON}=30°C T_{EV} =10°C

Figure 4.9 shows COP of simulation (typical day 1 April) and COP of experimental measurement (1 April 2011) with time. The result revealed the level of correlation vis-a-vis the simulation weather data of 1 April cycle gotten from www.weatheranalytics.com and the actual weather of Zaria on 1 April 2011. The simulated COP increases with time to a maximum of about 0.9 and assumes a dome shape. While the experimental COP increases similarly to a maximum point of about 0.85. If the COPs are compared on an average bases, there may be a perfect agreement. Here the experimental profile follows a similar pattern, hence, there is a good agreement between the simulation and experimental results. The relative agreement of the simulation and physical experiment are shownin the Figures 4.8-4.9. Moreover, Figure 4.10 shows the variation of simulated (1April cycle) and experimental (1April 2011) COPsolar with desorption temperature. In comparison, the simulated COPsolar increased with increase in desorption temperature. While the experimental COPsolar decreased with increase in desorption temperature close to the boiling point (100^{o}C) of the refrigerant (water) from where it again increases. The COPs are not in good agreement at temperatures before actual desorption temperature of the refrigerant.

The COP's are in agreement at desorption temperatures closed to the boiling point. Within the experimental desorption temperature used, the simulated COP's is much higher than the experimental values.

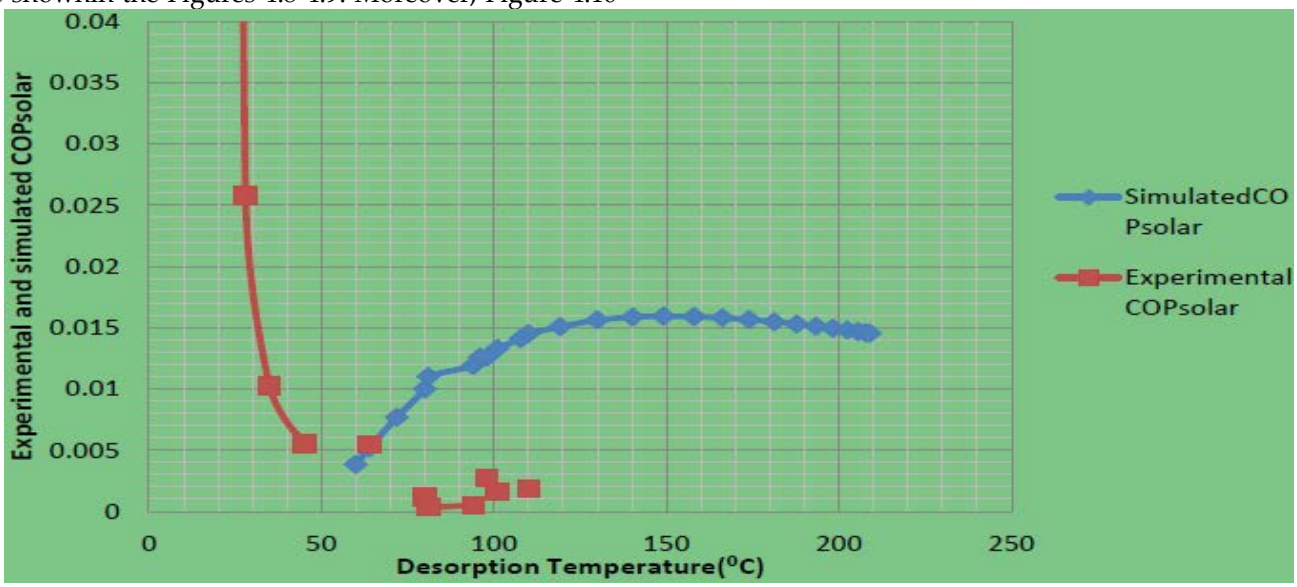

FIGURE 4.10 VARIATION OF SIMULATED AND EXPERIMENTAL COPSOLAR WITH DESORPTION TEMPERATURE (1 APRIL CYCLE).

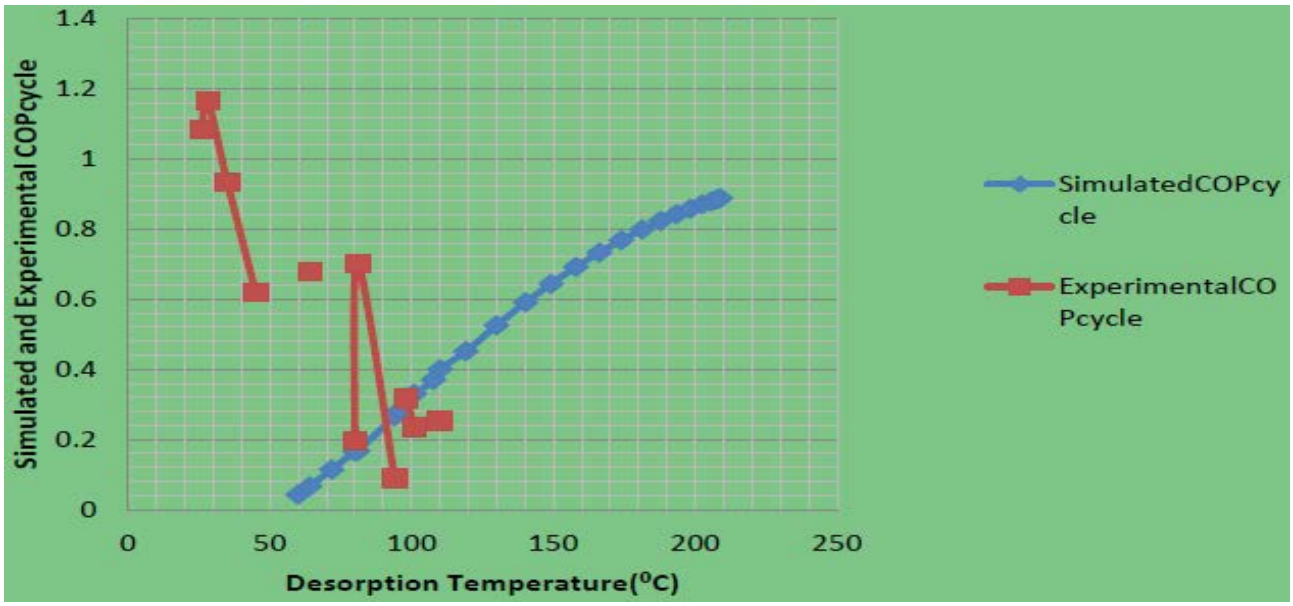

FIGURE 4.11 VARIATION OF SIMULATED (1 APRIL CYCLE) AND EXPERIMENTAL (1 APRIL 2011) COPCYCLE WITH DESORPTION TEMPERATURE.

As seen from the graph, the cluster of experimental COPsolar values for various desorption temperature is within 0.001 and 0.0035. Furthermore, Figure 4.11 shows the variation of simulated (1April cycle) and experimental (1 April 2011) COPcycle with desorption temperature. In comparison, the simulated COPcycle increased with increase in desorption temperature. While the experimental COPcycle decrease with increase in desorption temperature close to the boiling point (100^{o}C) of the refrigerant (water) from where it again increases. The COPs are not in good agreement at temperatures before actual desorption temperature of the refrigerant, while in agreement at desorption temperatures close to the boiling point. In contrast to Figure 4.10, the cluster of experimental values (COP's) for the COPcycle within the experimental desorption temperature is between 0.2 and 0.35. The previous night cooling effect is responsible for the high COP's values prior to the actual desorption temperature as shown in Figure 4.11.

Validation of Experiment

The model and actual experiment coefficient of performance from 1 to 14 April cycle are presented in Figure 4.12. The COP values fluctuate between 0.8 and 0.9 for both simulated and physical experiment within 1 to 14 April period. From the results, it was observed that the profiles follow the same pattern except for overlaps in some areas. The theoretical assumptions may be responsible for these differences. The simulation assumed no loss which cannot be true. Equally, the efficiency parameters of a commercial design having a different geometry serve as input data for the simulation.

Also, the output temperature from the collector may not be the same with the adsorber bed temperature as assumed. In order to validate the actual experimental results with the simulation results, the variance in performance for the period was examined, Figure 4.12 to determine the correlation between the simulation and experimental results. The data has revealed the difference between the ideal and actual COP. On an average, the level of disagreement is not more than 5% for a typical year in Zaria. Hence, the collector model performance is closed to the actual performance. Therefore, the results can be used to predict the performance of a zeolite4A-water adsorption refrigeration system.

Conclusions

In conclusion, the comparison of the designed, constructed and tested system experimental measurements and the numerical simulation results of the same Zeolite 4A–water adsorption refrigerator as presented showed that

1 The experimental and simulated COP (theoretical) result agreed satisfactorily and conformed within the range of 0.8-0.9.

2 TRNSYS predicted and obtained experimental readings of ±2.5%

Hence, TRNSYS simulation prediction can be used for the design of zeolite 4A-water adsorption system.

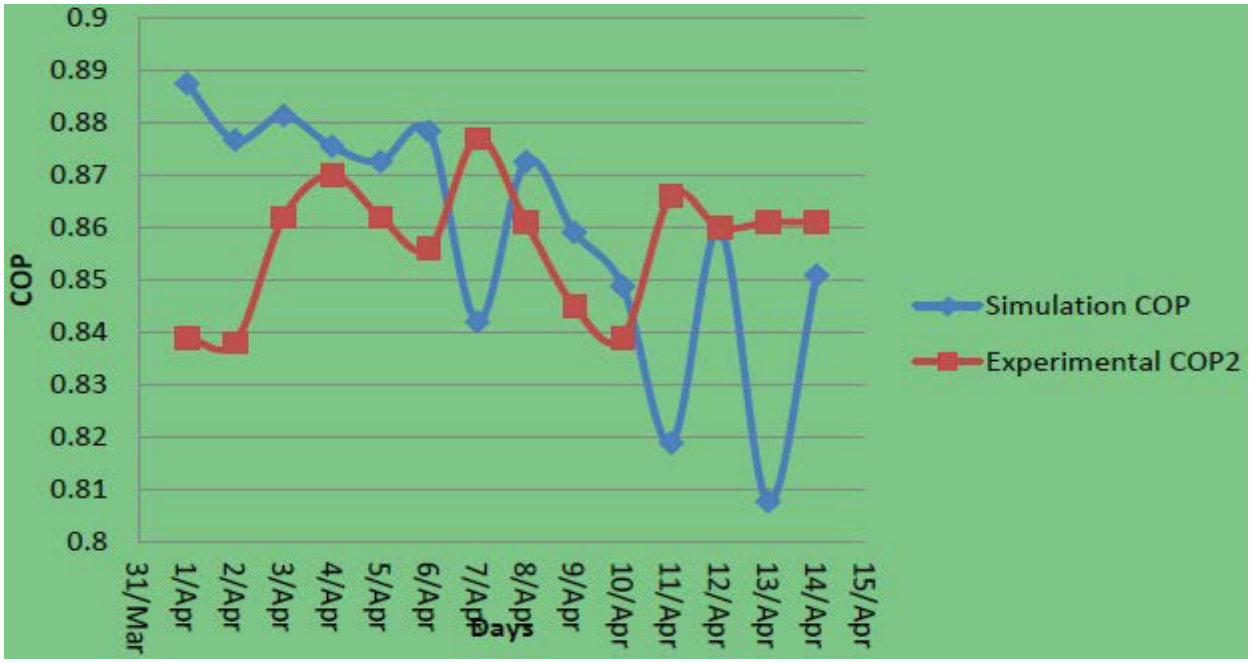

FIGURE 4.12 VARIATION OF EXPERIMENTAL AND SIMULATION COP WITH DAYS (1 TO 14 APRIL CYCLE).

ACKNOWLEDGEMENTS

The authors appreciate TRNSYS software, materials and equipment assistance provided by the Department of Mechanical Engineering, ABU Zaria, as well as the assistance of these individuals, Mal A Yakubu, Abduljelil Iliyasu, and others numerous to mention.

NOMENCLATURE

A_r	Absorber tube (receiver) surface area (m^2)
A_a	Collector surface area (aperture) (m^2)
c_p	Specific heat capacity at constant pressure (J/kg K)
h_{sg}	Isosteric heat (kJ/kg)
k	Thermal conductivity (W/mK)
L_{ev}	latent heat of evaporation (kJ)
m_r	Mass flow rate (kg/s)
Q_{sh}	Sensible heat of adsorption (kJ)
Q_{des}	Heat of desorption (kJ)
Q_{ev}	Heat of evaporation (kJ)
R	Universal gas constant (J/kgK)
T_{amb}	Ambient temperature, (^oC)

GREEK SYMBOLS

ϱ	Density (kg/m^3)
η	Thermal efficiency

SUBSCRIPTS

a, amb	Ambient
ad, a	adsorber
c, co, cond	condenser
d	desorption
dr	drainage pipe
e, eva	evaporator
fin	fin plate
g,gen	generator, generated
Qcoll	Insolation
Qucoll	useful energy
ref	refrigeration
sat	saturation
T_c	condenser temperature
T_d	desorption temperature
T_e	evaporator temperature
v	vapour
w	water
z	zeolite
COP	Coefficient of Performance
COPs	Coefficient of Performance solar
CPC	Compound parabolic concentrating collector
SCP	Specific cooling power
MATLAB	Mathematic laboratory
TRNSYS	Transient System Simulation

REFERENCES

Anyanwu, E. E. and Ogueke, N. V. (2004) Thermodynamics design procedure for solid adsorption solar refrigerator *Renewable Energy* Volume 30, Issue Page 81-96, Elsevier Ltd.

ASHREA (2003), SRCC (1995) ASHREA Handbook: Heating ventilation and air conditional Application SI, American society of heating Refrigeration and air conditioning engineers. publisher; Amer society of heating 2003.

Baker, D. K. (2008). Thermodynamic Limit to thermal Regeneration in adsorption cooling cycle. I*nternational Journal of regeneration*, vol. 31 (no.1), pp55-64.

Cacciola, G., and Restuccia, G, (1999) Adsorption heat pumps: a new way for energy saving and CFCs replacement. In: Dabrowski A, editor. Adsorption and its application in industryand environmental protection Vol. 120B. Amsterdam: Elsevier Science; Pp 949-978.

Critoph, R. E. (1988) Performance limitation of adsorption cycles for solar cooling, *Solar energy* 41, Pp 21-31

Duffie and Beckmann (2006) *Solar Engineering of thermal processes*, 3rd edition, university of Wisconsin-Madison, John Wiley and Sons, Inc

Floride, G. A., Kaligirou, S. A., Tassou, S. A. and Wrobel, L. C. (2000). Modelling and simulation of an absorption solar cooling system for Cyprus, *Solar Energy*, 72; 43-51.

Lucas,L.(1988) International Institute of Refrigeration News, *International Journal of Refrigeration*, 21(2) : Pp 88

Pons, M., and Grenier, P. (1986). A phenomenological adsorption equilibrium law extracted from experimental and theoretical consideration applied to the activated carbon - methanol pair *Carbon*, 24, pp 615 – 625.

Pons, M., Meunier, F., Cacciola, G., Critoph, R. E., Groll, M., Puigjaner, L., Spinner, B., Ziegler, F. (1999) Thermodynamic based comparism of sorption systems for cooling and heat pumping *Int. J. of*

Refrigeration 22: 5-17.

Shigeishi, Ronald A., Cooper, H. Langford and Hollebone, Baryan R., (1979). Solar energy storage using chemical potential changes associated with drying of Zeolite. *Solarenergy Journal* Vol. 23. Pp 489-495

TRNSYS 16 manual (2007) *Solar energy laboratory*, University of Wisconsin-Madison. Volume 1-9.

Wang, R. Z. (2001) Adsorption refrigeration research in Shanghai Jiao Tong University for refrigeration, *Renewable and sustainable energy review* vol. 5 pp1-37, 2001

Yong, Li and Wang, Ruzhu Z. (2006) Adsorption Refrigeration: A Survey of Novel Technologies. Recent patient on Engineering 2007, Vol. 1 No1 *Bentham science publication Ltd*.